

APPLYING NASA REMOTE SENSING
DATA TO GEOLOGICALLY RELATED REGIONAL
PLANNING PROBLEMS IN TENNESSEE

7.9-10095
CR-150866

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FINAL REPORT

CONTRACT #NAS 8 - 32034

(E79-10095) APPLYING NASA REMOTE SENSING DATA TO GEOLOGICALLY RELATED REGIONAL PLANNING PROBLEMS IN TENNESSEE Final Report (Tennessee Univ. Space Inst., Tullahoma.) 70 p HC A04/MF A01	N79-17289 Unclas 00095 CSCI 08G G3/43
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REMOTE SENSING IN THE GEOLOGICAL SCIENCES A COMPENDIUM

INTRODUCTION

This paper presents the results and conclusions of a series of two two-day workshops held at The University of Tennessee Space Institute in Tullahoma, Tennessee. The workshops were held March 10 - 11, 1978. The schedules of each are attached as Attachment 1 and 2, respectively.

This paper will be organized into chapters in much the same way that the material was organized by the original speaker at the workshop. The styles of the different authors are in general, retained, but the present author has freely edited and compiled to cut down the volume of material presented.

In general, the consensus of opinion by all speakers was that the use of remote sensing technology has indeed gone beyond the experimental-introductory stage in the world, nation, and in Tennessee. Remote sensing has daily functional uses in every scientific discipline, with more discovered every day. Geology, as a strongly spatial and also temporal science, perhaps has the most use of remote sensing of all the physical sciences.

Perhaps, however, the greatest benefit derived in the workshops is not even included in these pages. The gathering of geologists and physical scientists from different disciplines, agencies, and areas promoted the free exchange of material, ideas, problems, and successes in the utilization of the remote sensing in the task of studying the earth and the processes that operate upon it.

Remote Sensing - General

In the Manual of Remote Sensing published by the American Society

of Photogrammetry the following definition of the field of remote sensing appears:

"The field of remote sensing may be defined very broadly to encompass techniques that obtain reliable information about the properties of surfaces and objects from a distance." This may be accomplished by measuring electromagnetic radiation emitted by or reflected from the surfaces or objects. The surfaces of objects of primary interest in aerospace-oriented remote sensing are terrestrial resource or environmental features. The vehicles bearing the sensors are aircraft or spacecraft and the distances from the sensor to the scene are measured in terms of miles. It is with the electromagnetic radiation (EMR) aspect of remote sensing, that which is emitted by or reflected from the ground scene to the sensor in the vehicle, that we are concerned.

It is with light in the visible and near infrared range that remote sensing is mostly involved. Thermal IR sensing has also been performed, as has also radar surveying. The principal instruments have been the camera, both film and television, the IR scanning radiometer and the radar scanning instrument. In camera utilization both single-band wide spectral coverage cameras and narrow-band multispectral cameras have been active.

Film in a camera is the most commonly used detector of measuring visual frequency radiation.

Remote sensing is a new field in the sense that World War II and its aftermath contributed such significant technical developments that the means used today for world aerial mapping are substantially different from those in use before the war. Prior to WWII, an aerial film camera loaded with black and white film and mounted in a twin-engined Beechcraft represented the state of the art. Such equipment is still used and is an important element in remote sensing. Today, however, huge areas of

South America, formerly closed to aerial survey by continuous cloud cover, are mapped by radar mounted in multi-engined turboprop or turbojet aircraft flying at altitudes sufficient to give broad, yet economical ground coverage. Satellite coverage is also available. Portions of the electromagnetic radiation spectrum from which important information about earth resources can be derived were formerly closed to aerial survey because the radiation did not fall in the visible spectral region, and the film was not sensitive to it. Present day solid-state electronic devices can be made sensitive to such radiation and form a significant part of remote sensing equipment.

Remote sensing, then, simply put, is "detecting from a distance". This detection is made possible because of electromagnetic spectral and spatial factors enhancing the contrast between an object or item of interest and its background.

Environmental Analysis

As applied to man's environment, remote sensing is concerned with gathering information related to the quality, protection, and improvement of our land, water, and air resources. Of special interest are the detection of changes on the environment brought about by natural and man-made phenomena and the measurement of pollution of our resources. Remote sensing techniques from satellites and aircraft are directed toward what can be sensed in the environment, the environmental impacts of man's activities, how the changes in the environment affect our way of life, and how we can restore or improve a damaged environment.

Using remote sensing, such tasks as monitoring strip mining and reclamation, assessment of changes in urban quality, measurement of damage by pipeline construction, and many more involving land and vegetation quality can be achieved. Also, problems concerning water quality, such as measurements of suspended solids and chemical wastes, indirect determination of chlorophyll, and detection of large-scale ocean dumping can be achieved.

From such satellites as Landsat, data is obtained for use in managing wildlife, in detecting smoke plumes, and in determining the influence of air pollution on climate and weather. Detection of urban haze and atmospheric aerosols may also be accomplished with Landsat data. We will speak further of environmental assessment via remote sensing later.

Crop Classification

Because of the size, remoteness, diversity, and vulnerability of the world's crops, accurate information on production during and following the crop season, is limited to the crops grown in the more

advanced countries. One promising means of meeting the current and future needs for crop information is remote sensing. Conventional, medium-scale aerial photographs have been used for decades in some regions for identification of major crops and monitoring of crop-area allotments. The use of more sophisticated techniques (e.g., high-altitude color photography, multispectral scanning, and earth-satellite imagery) offers the potential of large scale agricultural surveys. The first step in the classification of agricultural land is that of learning to recognize broad categories that are easily separable on conventional photographs. In many regions of the world, the following six categories can be identified: seasonal row crops; continuous-cover crops; improved pasturelands; fallow or abandoned fields; orchards; and vineyards. It is also usually possible to differentiate between irrigated and dry farming areas.

Agricultural Epidemics and Plant Disease Detection

Losses due to floods, wind storms, or droughts are minor compared to those resulting from plant diseases. Damage may begin when the crop is planted, continue throughout its growing period, and persist after harvest, when products are transported and placed in storage. Unless diseases are prevented or controlled, there can be no sustained improvement in crop production. The economic gain from early disease detection is that of effectively increasing agricultural productivity. To employ fungicides or herbicides effectively, the agriculturalist must have sufficient advance warning of disease incidence, severity, and rate of spread. This need for immediate diagnosis and control has resulted in numerous research studies aimed at previsual detection of plant vigor losses. These studies have been carried out with remote

sensing using infrared color photography. The reason for this appears to be that many diseases result in a decreased reflectance of plant foliage in the near-infrared portion of the spectrum.

Irrigation Reform and Practice

Forecasts of available water resources have substantial economic value to irrigation farmers who must plan the coming season's crops, to power companies whose schedules of water release from reservoirs become increasingly efficient with better knowledge, and to many other water users. The economic and social value of good forecasts increases as fresh water becomes scarce and as flood plain occupancy becomes more intensive. A remote sensing system can materially assist in the maintenance and operation of existing irrigation systems. Remote sensing techniques could also be used to advise farmers on irrigation timing and water quantity. For a known soil and drainage condition, it appears probable that certain remote sensors will be able to detect the changes in surface moisture with enough confidence that water table depths can be deduced.

Soil Surveys

Soil surveys constitute essential information for sustained agricultural production. For all practical purposes, soil characteristics determine the type of crop that can be grown and the production potential of that crop. As outlined by the National Academy of Sciences (1970), information on soils is particularly important in an area in which new land is being brought into production.

Remote sensing plays an important part in soil surveys. Until recently, soil surveyors have relied on conventional panchromatic photo-

graphy, in conjunction with large amounts of field work, to delineate soil boundaries. However, more promising and reliable results are now being obtained with color photography and multispectral scanner imagery. Photo scales of 1:6,000 or larger are usually preferred, and aerial flights are ideally scheduled soon after agricultural fields have been plowed.

Hydrological Problems

Hydrology is the applied science concerned with the inland (fresh) waters of the Earth - their occurrences, distribution, and circulation through the hydrological cycle. The more information the water manager has about the hydrologic cycle, the better he is able to allocate water resources for consumption, industrial uses, irrigation, power generation, and recreation. In times of excess, flood control becomes the primary task; otherwise, drought, irrigation and power generation are the primary concerns. The broad area and time perspectives gained by satellite remote sensing add significantly to the conventional hydrological data collected at point measurement stations. It is fortunate that many of the hydrologic features of interest for improved water resource management are easily detected and measured with remote sensors. Snow is easily distinguished from soil or vegetation or liquid water, so amounts of water stored in solid form during the winter are easily distinguished and can be readily monitored. Results indicate that important contributions to understanding the hydrologic cycle are possible using snow and ice mapping, surface water inventories, flood assessment, and water quality monitoring.

Snow Cover Survey

Snow cover mapping is carried out by or for various groups that

supply and control water, such as irrigation districts, hydroelectric power developments, and others, for the basic purpose of prediction of expected runoff in streams deriving at least part of their water supply from snow melt. Some of the items of interest in mapping snow include (1) extent of snow cover, (2) elevation of the snowline in mountainous terrain, (3) snow depth and (4) water equivalent of the snow pack. Remote sensing represents that only feasible means of obtaining this type of data. Accordingly, snow distribution measured by aerial survey has been carried out by various groups for some time, especially in the mountains of the western United States.

Flooding

The recording and prediction of floods are important to millions of people who live and work along flood-prone rivers and shorelines. Urban development in flood-prone areas have created the need for careful planning and management by local, State, and Federal agencies. Accurate, rapid, and economical methods are needed to provided the data necessary for planning management functions. Flood mapping involves many facets of engineering, geology, and hydrology, remote sensing techniques have been utilized for many years in studying floods, but recent study and technique development has extended the scope of the potential use of remote sensing. Aerial photography has been used primarily for supplemental data, such as historical documentation of the crest of occasional floods.

Meteorological Satellite Systems

Although satellite borne remote sensors are not the only remote sensing systems, they are currently the most important to meteorology. NOAA operates two systems, the Geostationary Environmental Satellite (GOES)

and the Improved TIROS. The USAF operates the system Defense Meteorological Satellite Program (DMSP).

Site Investigations

Remote sensing techniques have been utilized for a variety of engineering site investigations. These have ranged from large area-investigations, such as the location of cities and towns, to more limited areas of investigation, such as the location of bridge sites, dam sites, power plants, parks, malls, sewage disposals, and tunnels. In all of these investigations the goal is to locate a site which is the most economical to develop, which would incur a minimum of disturbance to the natural terrain and cultural features, and which is exposed to a minimum of hazards. The procedures followed in the performance of site investigations for engineering structures closely parallel the stages taken for highway location.

Techniques of remote sensing have been used successfully in nearly every facet of geology in geologic hazard monitoring and analysis, in physiography and geomorphology, in economic geology from discovery to reclamation monitoring, in hydrology, and in environmental monitoring and structural geology.

For remote sensing to be of use in geologic or other physical science research, several criteria must be satisfied: 1) One must generally be looking at or for large features that need a regional view for identification or clarification. Many large features have gone unnoticed because of their very magnitude. An example, familiar to each of us here, of the importance of scale in the use of remote sensing data is represented by images made in West Tennessee from different altitudes and with several different resulting scales. Each image has had its own use. 2) A second factor rendering remote sensing useful to geology is the temporal basis which may be established. Landsat 1 and 2 can give temporal data on a nine-day basis. Examples of this temporal requirement are found in glacial geology and in coastal landform and sediment transport studies both along the coast and inland. 3) A third factor that may occasionally give remote sensing value occurs when atmospheric conditions on rough terrain make ground truth data collection difficult. A good example of the atmospheric condition problem is in the topographic mapping of cloud-covered Panama, by the use of radar imagery. This particular sensor is not hampered by the cloud cover. 4) A fourth factor that makes remote sensing a natural tool for utilization in geology is area perspective in support of local observation. Geologic mapping by remote sensing data alone has been proven time and time again in the literature to be quite difficult. However, when used with ground truth and/or prior

knowledge of the area, remote sensing data can be a powerful ally to customary ground surveys, as in delineating boundaries and in checking maps.

The geologic profession has always been progressive in the use of new geophysical tools, such as seismic and resistivity instruments, magnetic and gravity surveys, gamma-ray and neutron instruments for down-hole information, and the use of x-ray and magnetic equipment in identification. The wide variety of research next to be reported will show the search for utilization of the new science, remote sensing, in aiding in the solving of geologic problems.

REMOTE SENSING APPLICATIONS
IN GEOLOGY

I. Remote Sensing - Mississippi Alluvial Plain

A. In the presentation, the nature of the alluvial plain was studied by looking at sets of photos and maps. Illustrations consisted of maps and photos mounted on the walls as displays, 35 mm slides and hand out sheets.

The main components are:

1. Mississippi River
 2. Alluvial Plain
 3. Bluffs at edge of plain
 4. Linear features that perhaps are faults or cracks
1. The Mississippi River constitutes a depositional system which involves the channel and alluvial plain.
 - a. Bar, chute, natural levees along river channel
 - b. Overwash and slack deposits on the alluvial plain
 2. Ancient deposits (visible on the alluvial plain) had a similar system.
 - a. Old channel fills
 - b. Natural levee deposits
 - c. Ancient overwash

Much is buried beneath younger river deposits; but some areas underlaid by ancient deposits are uplifted, judging from their high elevations above modern flood levels.

3. Bluffs are mainly made of loess which is being eroded and the eroded material being deposited on the alluvial plain as fans. Fans occur west of valleys, the bigger the valley

the bigger the fan. Landslides are also characteristic along the bluffs.

4. Lineations occur in all parts. Earthquakes occur today and modern deposits appear to be affected, as well as upland.

B. Selected photos and maps showing features were furnished to participants so they can keep them for reference and work on them.

1. Participants can hopefully:

Map bluffs, landslides and alluvial fans

Map depositional areas and interpret sequence of events along the modern river

Interpret lineations on uplands and flood plain

2. List of hand-out maps and photos is as follows:

- a. Topographic map of the inside of a bend in the river opposite Caruthersville, Missouri. This map shows over-wash topography to the north and bar and chute topography to the south.
- b. A USDA soil map showing soil patterns and photo imagery of part of the area of a.
- c. An ASCS photo in Tipton County, Tennessee showing later left banks of the Mississippi River having cut into earlier deposits. Natural levee "distributory rill" patterns are clearly shown even on this low-quality print. (The presentation is interrupted here so participants can see displays and work on a, b, c)

- d. Topographic map of the Tiptonville "dome". Its east edge is an east-facing slope (supposed fault scarp) that forms the west shore of Reelfoot Lake and extends northward past Proctor City. To the west by Island No. 12 arcuate cuts show earlier left banks of the Mississippi River (as in c).
 - e. A USDA photo just north of d. An arcuate small stream course marks an earlier Mississippi River Channel. A natural levee of the Mississippi River and arcuate cuts are visible to the northeast.
 - f. A USDA photo showing earlier Mississippi River courses on upland. This photo is just north of d and west of e. (The presentation is interrupted here again so participants can work on d, e, f.)
 - g. Topography of the Ridgely Area north of Madie, an old Mississippi River course, runs east-west.
 - h. & i. Photos of false color infrared originals in the area of g.
 - j. & k. USDA soil maps also of the same region as g (linears and old Mississippi River courses can be seen here). Light areas are commonly sand blows. Soil patterns reflect old Mississippi River courses.
- (This terminates the presentation; participants can see displays, work on g, h, i, j, k, and continue discussions.)

II. Remote Sensing in Strip Mine Enforcement

Extraction of near-surface coal by surface or "strip" mining techniques is an economically feasible response to the Nation's growing energy demand. In order to reduce dependence on foreign petroleum imports, coal mining activity has increased greatly in the past few years, and will continue to do so as new reserves are opened. The Nation's need for energy, however, must be balanced with the environmental consequences of coal exploitation. Surface mining un-accompanied by reclamation renders the land barren and non-productive. Property near or adjoining mine sites is degraded in value, and severe erosion, flooding and air and water pollution may also occur.

Of the estimated 2.2 million acres of land stripped for coal in the United States, only a third has been reclaimed (Council on Environmental Quality, 1974). National reclamation standards do not yet exist and requirements vary widely among the 23 states which presently regulate strip mining. Thus, information on the location, size, and condition of mines is often lacking or inadequate. Therefore, it is important to have an effective capability for monitoring the areal extent of stripping, detecting the areas adversely affected by acid mine drainage, and assessing the effectiveness of reclamation and pollution abatement procedures. Because of its repeated complete areal coverage, Landsat data provides a potential means of routinely monitoring and evaluating strip mining and reclamation procedures in any region of interest.

Under contract for the Tennessee State Planning Office, imagery relayed from the NASA Earth Resources Technology Satellite (Landsat 1) was applied to monitor strip mines in the New River Drainage

Basin in East Tennessee. This was a cooperative NASA/UTSI effort to encourage a transfer of aerospace technology to state use. The primary objective of this study was the application of satellite data in the monitoring of surface mines.

Landsat Data

The repetitive Landsat coverage provides an excellent monitoring system to map strip mining areas. These images are available at a scale of 1:1,000,000 in four wavelength bands from visible through infrared with the following characteristics:

- o Band 4, the green band, 0.5 to 0.6 micrometres, emphasizes movement of sediment laden water and delineates areas of shallow water, such as shoals, reefs, etc.;
- o Band 5, the red band, 0.6 to 0.7 micrometres, emphasizes vegetation, the boundary between land and water, and landforms; and
- o Band 6, 0.7 to 0.8 micrometres, spans the border between the visible and the near infrared regions of the spectrum and is particularly suited to identify difference in land use and to sense the amount of green biomass in vegetation.
- o Band 7, the second near-infrared band, 0.8 to 1.1 micrometres, provides the best penetration of atmospheric haze and also emphasizes vegetation, the boundary between land and water, and landforms.

Work indicates that bands 5 and 7 appear to be best for regional mine land inventories.

Landsat imagery is useful for detecting changes resulting from active mining and from land reclamation developments. The spatial resolution of the imagery is, however, a significant problem, particularly for small areas of only a few hectares. Since one pixel element is almost 0.5 hectare (1.12 acres) in size, the averaging of energy in a pixel that extends across a boundary

of mined and non-mined land can produce erroneous area measurements of substantial dimensions. The larger the mined area, the smaller the percentage of error that will be encountered. Hence, the potential for the application of Landsat imagery to mined land monitoring is greater for states with area mining than for states with contour mining.

The discrimination of mixed land features is somewhat limited on Landsat imagery. For instance, it is difficult to identify land disturbed by actual mining and other associated activities, particularly the systematic removal of vegetation in advance of actual stripping operations. Also, as mixed land is revegetated, it blends into the non-disturbed land and is difficult to identify. The final results of a UTSI-TSPO study showed that:

At present, it appears that for most state requirements for around-the-year, surface mined land monitoring, Landsat is limited value. However, for periodic, e.g., yearly updating of regional surface mine maps, Landsat may provide sufficient accuracies for some users. With appropriate baseline data, Landsat can provide information rapidly and economically for updating progress of new mining and reclamation of mined land. At this time, the advantages of Landsat mentioned in the previous sentence are of prime concern to Tennessee agencies involved in mining activities.

Dr. John Rehder of the University of Tennessee showed that Landsat was most valuable in detecting change. He compared Landsat with RB57, low-level aircraft, and ground truth data sources.

REMOTE SENSING APPLICATIONS
TO LINEAMENT SURVEY

(1) Definitions

Lineaments were defined by Kaiser as early as 1950 as straight linear surface features at least hundreds of feet long (commonly miles long)". Later definitions by Lattman (1958) limited lineaments to one mile plus in length, and those less than one mile he referred to as fracture traces.

In a comprehensive paper on Lineaments and linears in the minerogenic province of Southeast Missouri, Hasan El-Etr differentiated between fracture traces (which he said were interpreted as airphoto linears, and were generally less than one mile long) and lineaments, which are more regional in character.

Saunders and Hicks of Texas Instruments, in a recent paper on the relationship between basement tectonics and lineaments, define linears as those linear or gently curved alignments of topographic features or tones identified on satellite imagery, while lineaments are those groups of linears thought to have tectonic significance. In this report, circular or subcircular curved features are termed curvilinears.

So, while differing somewhat, the definitions have some things in common. This author's composite definitions are:

Linears--straight linear features, generally visible on hyperaltitude or lower photography, and probably representing fracture traces or joints. Generally less than one mile.

Lineaments - Linear features, more than one mile in length, interpretable from satellite imagery, those more than 10's of miles in length, probably are the surface expression of deep-seated planes of basement weakness.

Curvilinears - Circular or semi-circular, curved features, in places representing surface expressions of such features as domes, ring dikes, cauldernas, intrusive stocks, or astro-blemes. These definitions are those which will be used during this presentation.

(2) Factors that cause linear interpretations

What features actually cause linear features to show up on imagery or photography? Lineaments are generally really a series of short, identifiable features that can be interpolated into a single trend. Real, identifiable parts of the lineaments may be:

1. linear topographic features
2. linear vegetative patterns
3. linear patterns of soil color or texture
4. stream segments, valleys, or gaps that are aligned
5. the straight side of ridges (similar to #1)
6. land use patterns

An interesting study is one in which one takes lineaments defined on Landsat satellite imagery, then enlarges those features to fit hyperaltitude and even 7½ minute quadrangle scales - actually identifying what caused your eye to see a linear feature can get fuzzier the closer you get to the ground. For the most part, however, one can see at least

portions of the linear feature, and can determine what made one draw the feature.

(3) Techniques used to detect lineaments (linears)

There are about as many methods of annotating lineaments as there are interpreters. Moore, in a Central Tennessee ground water study, used Skylab photography to detect lineaments. The steps he used were:

1. enlargement of original photos (in his case, to 1:480,000)
2. examine stereo-pairs of film transparencies by a stereoscope on a light table
3. project photos on the wall, and use a "Ronchi ruling" (unit 150 lines/inch) against the lense to enhance lineaments
4. check lineaments on hyperaltitude photos
5. transfer lineaments to a base map

Saunders and Hicks were mainly interested in very large scale (more than 100 mile) lineaments, so they worked with composite Landsat imagery at scales of 1:1,000,000 and 1:2,500,000. They used MSS bands 5 and 7. Lineaments were drawn on band 7 on a back-lit mosaic on a light table, then checked against band 5 imagery. This is done because man-made linear features, such as roads, railroads, power and pipe-lines show up on band 5, and can be eliminated.

Many other techniques are used in an attempt to enhance lineaments to make them more obvious and easier to interpret. Among them are various lighting techniques - reflected and/or

refracted light, light tables with film products, or overhead lights with opaque photo products. As mentioned above, a Ronchi grating (simply an accurate grid of lines) placed over the lense of a projector projecting a picture, then slowly rotated tends to enhance the lineaments that parallel the grid as it rotates.

Several observers have noted that snow cover tends to enhance lineaments. This would be particularly true in the case of topographically-expressed lineaments.

El-Etr noted that he was able to interpret more lineaments with natural light, outdoors. Some observers used photos in conjunction with plastic three-dimensional relief models. Some have observed that curvilinears show up best when observed through a reducing glass (similar to a magnifying glass, only the lens is reversed - a common draftman's tool).

The computer and scanning devices have been used with fair success in some places - generally the technique used involves overlay of film positives, then rotating the films and digitizing at each rotation. This technique seems to enhance lineaments. The interpretation of linear features in many ways is an art rather than an exact science. An art that must be carried on within definite rules and guidelines, but the human subjective look is essential. Machine help on the front end, in enhancing photos to help you look, and at the back end, to statistically handle interpreted data, can be a tremendous help.

The author's technique in Lineament analysis:

1. start with a Landsat band 7, B&W, scale 1:250,000
2. interpret the lineaments - several settings -
not all at once - rotate many time, use different
lights
3. transfer to base map
4. if hyperaltitude is available, change scale and
further proof, refine, and better locate lineaments
5. prepare map

(4) Causes of Lineaments

El-Etr states that lineaments fall into two classes - primary lineaments (formed contemporaneously with the rock) and secondary lineation (formed after consolidation and lithification of the enclosing rocks). Primary include - flowage in igneous rocks, growth of minerals, and depositional and diagenetic structure (e.g., bedding, cross-bedding, graded-bedding, slump and turbidity structures, unconformities.

Secondary include - these related to rotation (folding, flexing) growth of minerals (post-lithification), geomorphic features (topography, physiography, drainage), erosional features and non-imposed features, and most important, intersection and movement and slippage along basement rocks.

Saunders and Hicks carry the theme out a little farther. They state that the regional system of lineaments (100 miles plus) are the surface expression of Precambrian, deep seated planes of weakness which divide the continental crustal plate into blocks. These basement faults caused a prominent ESE

striking set of lineaments, generated by transform faulting, beginning in early Precambrian with a sea-floor spreading event. Other strike sets of lineaments are thought to have been generated by subsequent (generally E-W) compressional stresses, causing transcurrent faulting and simple-shear block faulting along these other directions. Saunders and Hicks note that many of the lineaments may be traced across surfaces covered with sediments such as glacial drift and alluvium, and unconsolidated coastal plain sediment, thus lending support to the hypotheses that the basement fractures are repeatedly subjected to minor tectonic stresses (like earth tides) which propagate the planes or zones of weakness up through the sedimentary section to even exert control over drainage development.

So lineaments are obviously hooked closely to tectonic events. The payoff for all this, is that the lineaments show characteristic relationships to the locations of known petroleum and mineral deposits such that they can be useful as an initial reconnaissance tool in prospecting. Porphyry copper and other types of base and precious metal deposits are observed to occur preferentially along regional lineaments and at their intersections. Stratiform uranium deposits and petroleum fields show similar relationships to the lineaments. All of these can be logically explained by the effects of various lateral, vertical and intrusive stresses reacting on the ancient tectonics system of lineaments and blocks over geologic time.

Saunders and Hicks conclude that lineaments are of primary importance in controlling tectonics, sedimentation, and mineralization.

Many mineral deposits have been observed to occur along and adjacent to prominent lineaments. A paper written in 1941 related mining districts to structural trends and their intersections. Most of the mineral deposits in the western U.S. lie along lineaments and intersections. In the area around Salt Lake City, it has been shown that all of the base metal and precious metal districts, including Bingham Canyon, occur at lineament intersections.

In Missouri, El-Etr concluded that the lead zinc deposits of Southeast Missouri were:

1. lead of an epigenetic-hypogene origin
2. channel ways for mineralization followed one or more directions of the four regional lineations of the basins of sedimentation, and the trends of the linear primary and diagenetic features of the sediments
3. the lead deposits are controlled by the primary linear structural features which reflect the lineation pattern of the basement and by buried Precambrian knobs (with their local fracture patterns), and the regional fracture pattern of the sediments which is essentially similar to that of the Precambrian basement. This also applies to the Precambrian iron ores and the rich "runs" of the residual barite deposits in the Province.

In other words, the ore solutions moved upward from depth through fractures, linears, and/or lineaments in the Precambrian rocks and then up dip along unconformities, through a pervious sandstone and through fractures in this formation (having essentially the same alignment as those in the Precambrian basement) until they intersected the base of a more chemically reactive formation where they were further controlled by zones of maximum porosity and permeability (due to lithologic and/or structural factors).

It is believed by most writers that satellite-derived geomorphic lineaments provide the best deformation of vertical zones of permeability or crustal weakness, which can act as mineralizer channels, or preferred spots for igneous intrusion, this providing potentially better guidance in reconnaissance prospecting.

Considerable work has been done to compare linears and lineaments with known structure, fracture traces, joints, etc. A considerable amount of work has been done with joint traces, and joint orientation studies in the field, and more recently (since 1957) with fracture traces. Including ground based and aircraft overflight data there are least six of linear features, and while there is a link between joints and fracture traces, theory suggests that the same mechanism may link all scales.

Fracture traces, per se, may be revealed by straight valley segments, abrupt changes in valley alignment, gaps in ridges, gulley development, aligned sink holes and swallow

holes, localized springs and diffuse seepage areas, localized vegetational differences, etc. Fracture traces and lineaments are commonly straight, unaffected by topography, and hence are considered surface manifestations of vertical to near-vertical zones of fracture concentration

Parallelism has been recognized between fracture trace orientation and joints in relatively undeformed bedrock of Pennsylvania age of the Appalachian Plateau and flat-lying rocks elsewhere. The folded rocks fracture traces and joints have been found to have different trends. These authors found that joint sets are parallel and perpendicular to the strike of bedding, and that fracture traces are unrelated to local fold and fault structures. Dominant trends of fracture traces and joints differ; fracture traces appear to be unaffected by tight folds and tend to lie at a constant angle to regional structure. This work, together with that of many others, supports the conclusion that fracture traces and lineaments are not controlled by local structure but rather by regional features.

(5) How Compare?

A classic study is one by Knepper and others, done for the Colorado School of Mines. The handout shows briefly the products arrived at on the way to reducing the overall area

of search for new mineral deposits by some 95%.

The technique used by this author is very similar to that of Knepper et al.

1. Prepare lineament maps by the techniques mentioned earlier under lineament interpretation.
2. Prepare an overlay on the lineament map which shows only lineament intersections.
3. Randomly place a square grid (size depends upon scale of photo, density of lineaments) over the intersection map, and count intersection that fall within each grid cell.
4. Contour the numbered cells, producing a LIOM map (Lineament Intersection Cluster Map).
5. A secondary map might be produced combining intersection data with a qualifier (an average length of the intersecting lineaments - this puts the emphasis on the longer lineaments) as perhaps it should.
6. Compare with known deposits, structure, geophysics, drainage, whatever.
7. Not fool-proof--one more tool!

(6) The Use of Lineament Analysis in Geologic Hazard Work

Considerable amounts of research have been done in methods of using remote sensing data (particularly lineaments and their intersections) to help predict geologic hazard occurrences. Two good examples of this are in the study and analysis of ground stability in mining operations, and in earthquake prediction. These will be discussed separately.

A. Ground Stability in Mining Operations

Ground falls account for a large number of deaths and injuries in the United States mining industry each year. Geologic discontinuity in the Earth's crust contributes to this ground instability at mining level. The U.S. Mining Enforcement and Safety Administration (MESA) recognized the potential for using remote sensing techniques to identify hazardous ground areas in advance of mining. Satellite and aircraft imagery is used to evaluate this problem. Some very favorable correlations have been made between imagery signatures and ground stability problems encountered at mining level in past mining operations. From the analysis data, demonstrations have been made to mine operators showing the merits of implementing their own remote sensing analysis programs. Wide implementation of remote sensing for this application should lead to safer working conditions for miners.

Studies carried on around the world relating fractures, joints, lineaments, linears, etc., to underground mining, have shown the following:

1. Fault intersections contribute to zones of roof instability.
2. Density and characteristics of fracturing in roof rock can govern the intensity of roof falls.
3. Fracture systems provide avenues for migrating water which tend to weaken rocks intersected at the mine level.

4. Fractures may be the natural environment for clay vein formation; weak zones develop many times where clay veins are exposed to air by excavation.
5. Faulting can disrupt the continuity of a horizon or horizons being mined and require that a more difficult mining operation be implemented.
6. Surface drainage systems tend to follow fracture systems or zones of weakness. Fracturing associated with many drainage channels can contribute to ground instability when entries cut near or below these systems.
7. Roof falls and excessive rib spalling in coal have often been encountered when mining is being carried on parallel to the coal cleat system.
8. Bedding, schistosity, and fracture planes dipping into open pits and underground openings may result in ground failures.
9. Faults nearly parallel to the working face of an open pit can cause severe ground stability problems.

The use of remote sensing to provide additional data to help solve some of these problems, has shown that:

- A. Identify on the imagery known and suspected geologic discontinuities such as fault and fracture zones found in the areas of past,

present, and proposed mining activity.

- B. Recognize prominent linear intersections.
- C. Identify discontinuities in the proposed mining area in variable geologic environments such as areas of extensive unconsolidated overburden and areas where discontinuities intersect places of extensive riparian vegetation.
- D. Define major linear orientations and density pattern variations.
- E. Recognize surface lithology changes.
- F. Relate imagery linear features to surface and underground roof rock and coal joint systems where possible.
- G. Recognize hazardous subsidence over actively mined areas, especially if subsidence intersects water courses and engineered surface projects.
- H. Recognize tension crack development on the periphery of open pit mines.
- I. Locate man-made impoundments related to mining; monitor embankments for leakage and movement.

MESA has used these techniques successfully in about 30 mining sites around the country, in 14 states. The mines standard are located in a variety of geologic environments, and early results are encouraging. The data collected by remote sensing have indicated a real relationship to these problems.

B. Earthquake Hazards

A second type of geologic hazard that can be at least partially analyzed via remote sensing data is earthquake hazards and landslides. Remote sensing data has been used in many different ways in various studies of instability problems, such as damage assessment, amount of material moved, and other such data. In this instance, we are primarily interested in the use of lineament analysis in earthquake study.

Geologic structure is very important in earthquake, landslide and dam rupture assessment. This can be done through an accurate assessment of regional structure. Current crustal tectonic theory hypothesizes the Earth to have a dynamically-active shell. Proof of this is expressed not only in earthquakes but also in extremely subtle surficial changes which can affect drainage patterns and vegetative covering.

It is becoming increasingly important that we understand the mechanisms of earthquakes as much as possible. Recently, areas of Italy, Nicaragua and Guatemala have been devastated by large-magnitude earthquakes, all principally along known faults or fault zones. The magnitude 6.6 San Fernando, California earthquake of February 9, 1971 occurred along known fault surfaces.

- C. Except for some bedding-plane ruptures, surface breaks occurred mainly along faults that had been mapped

earlier. Few of these faults, however, were shown on published geologic maps. The perspective of orbital altitudes can be of great value in regional fault studies. Low-sun angle imagery acquisition and radar on an orbital platform may be desirable.

The results of many investigations by multi-disciplinary teams have indicated, however, a need for better spatial resolution in order to resolve certain geologic and earth resources problems. In general, it has been found in image processing the frequency resolution has been adequate from the digital data.

One of the greatest needs in geological interpretation is objective linear or lineament analysis; their presence profoundly affects large-scale construction projects. The recently launched LAGEOS satellite may give information on incipient earthquake activity.

Landslides occur in areas of slope instability or in areas of minor surface faulting where not only displacement and weakening has occurred but where groundwater is trapped. Landslides can be insidious, with barely perceptible movement, or dynamic with catastrophic results.

REMOTE SENSING IN WATER RESOURCE STUDIES

Utilization of remotely sensed data in hydrologic studies relies on simple qualitative observations which are made for example, the color of a factory effluent and quantitative information, including area, shape and length. Examples would include quantitative analysis of a drainage basin and channel network and the geographic location of fractures, faults and lineation. Correlations are also made between point measurements on the ground and some property of the remotely sensed data (e.g., density level of a spectral band). An example would be a study of density differences between two spectral bands on multispectral scanner data, permitting water depth to be mapped.

Lineament study has also been used to assist in the location of ground water supplies. Significant percentages of high-yielding wells are near lineaments, either classic lineaments as were discussed earlier, or elongated or aligned sink holes.

REMOTE SENSING IN WATER POLLUTION DETECTION AND MONITORING

Water pollution is one of the worst environmental problems today. Pollution occurs both in the oceans and in large and small inland water bodies. Unless ways are developed to detect and measure water pollution so man can control it, both our water supply and food supply could be destroyed. Remote sensing has been shown to be useful in helping to locate and measure some kinds of water pollution, but more remote sensing techniques need to be and are being developed to further aid in the control of water pollution. However, there are many problems that need to be solved before some of these techniques can be put to useful applications.

Some of the techniques not being used can produce $\pm 1^{\circ}\text{F}$ calibrated thermal discharge maps. Water quality maps consisting of chlorophyll, organic material, and turbidity concentrations and distributions can also be produced. Other uses of remote sensing include detection of chemicals and solid wastes in water and also the detection and mapping of oil spills. Presently surface materials can be remotely sensed by all forms of electromagnetic radiation including microwaves, infrared, visible light, and ultraviolet. All-weather remote sensing is provided by microwave radiation which can be used to map water surface temperature and roughness. Subsurface pollutants are hard to detect by remote sensing because water is transparent to electromagnetic radiation only in a rather narrow spectral region. This region includes blue and green light of the visible spectrum and is centered near 500 nanometers. Some of the

pollutants now detectable from satellites in space include major oil spills, large scale thermal emissions, and disturbances to beaches and estuaries. Five main uses are:

1. One of the main areas of water pollution that remote sensing can detect is that of thermal pollution. Since water is used as a coolant in many industries today, heated water is often returned to bodies of water. This can cause an increase in temperature of the original water source of anywhere from 2° to 10° C causing great damage to the plant and animal life. Infrared surveys can be used to determine this surface temperature rapidly over large areas. These surveys measure the temperature of the .1mm surface skin which is always cooler than that of the water 1mm below it. Also sensors aboard satellites have been used to map the thermal properties of the ocean surface.
2. Remote sensing can also be used to indirectly detect the presence of nutrient wastes in water caused by agricultural fertilizer runoff, detergents, and industrial wastes. Species of plants and animals, although not harmful by themselves, are indicators of pollution and can be remotely sensed while the water themselves cannot. Among the substances caused to be in excess by the nutrient wastes that need to be detected are excess phosphorous and nitrogen. These can cause excessive growth of algae and weeds which can cause a depletion of the oxygen content of the water and therefore kill desirable plants and animals in the water.

Algae blooms found in these over enriched waters can be detected by using false-color infrared film. Also, band 6 of Landsat gives a good correlation for the detection of algae blooms.

3. A positive correlation has been shown between optical densities on film and the turbidity in water. Color infrared film is used to eliminate bottom effects on the film densities. Detectors used include color, color IR, and multispectral film cameras as well as multichannel scanning radiometers.
4. The detection of oil spills is also possible by using remote sensing. The oil can be sensed in a large number of wavelength bands including the ultraviolet, visible, and microwave portions of the spectrum. Microwave radiometry is best suited for the initial detection of oil spills. It can be used day or night and even with some clouds. Since the oil initially floats on the water, its presence causes changes in the surface viscosity of the water.
5. The disposal of solid wastes is also a great environmental problem. Remote sensing can be used for monitoring and measuring sewage discharges. A rapid scanning spectrometer has been used to determine concentrations of solid wastes and to differentiate between solid wastes and other particulate matter in water. Film densities can be used to characterize and model the mixing zones of a river which are used to totally mix a waste effluent with the receiving water. Multi-spectral scanning imagery of Landsat can be used to measure ocean dumping.

However, current techniques of remote sensing cannot determine the exact content of the sewage or sludge because it is a mixture of many different substances. It can be determined that the pollution is there but no complete analysis of the contents can be made. However, it is possible to tell the differences between sludges that are from two different sources or cities. Only in rare cases can a positive identification of a pollutant be made by remote sensing, but it is possible to detect the point where the discharge reaches the body of water, where the discharge goes, and the general characteristics of its dispersion pattern.

There are four basic types of detectors used in the remote sensing of water pollution. They are the (1) imaging scanners which give a view of the scene outside the range of film emulsion, (2) imaging spectrometers which can eliminate background signals through prior knowledge of the spectral characteristics of the pollutant, (3) microwave, radiometers and radar which help to detect oil spills; and (4) regular film cameras. Film cameras operate at short visible wavelengths, and most record reflected sunlight on films which can cover the spectrum.

... These sensors are the most commonly used for the detection of various kinds of water pollution today. More are being and need to be developed to further expand the role of remote sensing in detecting water pollution. In the years to come better methods of remote sensing will be developed to interpret all the data that is being gathered. However, even now remote sensing plays a very important part in the control of water pollution.

3. Estuaries - the major problem today in estuaries is that municipal and industrial facilities are discharging waste faster than estuaries can assimilate them.

Navigable waters have become choked with sediment, resulting in eventual destruction of wetlands.

Many established and developing techniques of remote sensing have been used by investigators to improve insight into estuaries and inland wetland processes.

SUMMARY - THE USE OF REMOTE SENSING IN TENNESSEE

A summary of the use of remote sensing techniques that have been used in Tennessee is presented below, agency by agency.

1. East Tennessee State University - Dr. R. Peplies. One of the pioneer institutions in the use of remote sensing in geography and geology. Much of the work was pure research, and few technical reports were published. Work includes landslide detection in East Tennessee and Western North Carolina, traffic pattern detection, land use mapping.
2. University of Tennessee - Geography Department - Dr. J. Rehder. Considerable work has been done with remote sensing and wetlands. Landsat, hyperaltitude, and low-level photography has been used to map wetlands, and to detect change. Landsat imagery was used to map flood levels during 1973.
3. University of Tennessee - Engineering - Dr. B. Tschantz. Work has primarily been involving the strip and area mining regions of East Tennessee. The researchers have used Landsat, hyperaltitude color and color IR, radar, and plan to use thermal IR in future work, both in strip mine mapping, and in reclamation progress mapping.
4. Soil Conservation Service - E. B. Dyer. Soil Conservation Service has to be the largest user of conventional aerial photography that exists. In recent years, hyperaltitude

and low-level false-color infrared imagery has been used in crop mapping, disease detection, sedimentation monitoring, erosion control, and in land use mapping. Several specific projects that relied heavily on remote sensing included: the Chickasaw Basin Study, the Loosahatchie River Basin Study, the Obion-Forked Deer River Basin analysis.

5. University of Tennessee Space Institute - Dr. F. Shahrokhi. Probably the leading institution in the State in the remote sensing field. Remote Sensing Division has degrees available in Remote Sensing - offers short courses, seminars, etc. to business and industry. Several specific projects include strip mine reclamation project, wetlands mapping, erosion control, training sessions, and industry. Several specific projects include strip mine reclamation project, wetlands mapping, erosion control, training sessions, and land use mapping.
6. Tennessee State Planning Office - Has done projects with Appalachian Regional Commission on land use mapping, automated computer interpretation, and geographic data base analysis. State land use system utilizes considerable amounts of remote sensing data. Involved in a project with ARC to study lineaments and natural gas. Uses Landsat to prepare regional land use maps.
7. USGS (Pat Hollyday) - Beech Grove Lineament - Skylab prospecting for ground water-hydrology in Marland - Work in New River with SCS-Land Use and Mapping information - work with TVA in wetlands in West Tennessee.

8. TVA - Al Stevens - Land Cover mapping - Harrison Quad, 1:24,000 quad with USGS, county forestry maps, and a multitude of other photogrammetry and mapping-site checking, started by the Beech Grove Lineament controversy - now, TVA is using satellite and hyperaltitude data to map lineaments, - TVA is using geologic mapping, geophysics, and drilling to show relation to structure - now, at Saltillo and Yellow Creek and some North Alabama sites for PSARS - TVA is also using Texas Instruments Company on 2 sites to investigate the feasibility of photo-geologic mapping for initial studies pre-PSAR.
9. Vanderbilt- Work with earthquakes in West Tennessee; use of remote sensing in landslide project.
10. Consultants - beginning to use for land use maps - one very interesting study done by Bob Beavers near Franklin in which he used thermal IR to detect sites previously mines for phosphate to avoid unstable building sites for a new school. Several mineral exploration companies have used Landsat and hyperaltitude imagery to study lineaments, intersections, and their relationship to mineral deposits.
11. Tennessee Division of Geology - Ron Zurawski - The depository in Nashville for Landsat and hyperaltitude microfiche - has used remote sensing on several projects.
12. Tennessee Department of Highways - uses remote sensing frequently on projects such as the one described in this paper. A heavy user of conventional black and white photography.

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REMOTE SENSING IN GEOLOGY - GEOLOGICAL CONCEPTS

PART I

The study of geology has been one of the primary applications of satellite data and especially data from Landsat. Because of the large area covered by each image geologic features on a regional scale, which were only available in the past on generalized and sometimes inaccurate maps, have been observed. Examples of geologic features as seen from Landsat and from aircraft include:

Igneous Features - Examples of igneous features beneficially viewed in imagery are Crater Lake in Oregon, lava flows in Hawaii, spatter cones in Idaho, volcanic fields in Arizona, and the Great Dyke of Rhodesia. General features and drainage patterns associated with the various igneous examples may be seen clearly in the imagery.

Structural Features - Examples of various structural features are:

Folded Appalachian - the distinctive outcrop pattern of resistant rock types. Coal mine dumps and strip mined areas. Water gaps.

Cumberland Thrust Sheet area of Tennessee with examples of strike-slip fault and Pine Mountain Thrust fault.

San Andreas fault in California. The major associated faults and proximity to metropolitan areas.

Offset stream channels along San Andreas fault zone. Basin and range structures near Salt Lake City as defined by the Wasatch fault zone appearing as an irregular north-south trending scarp.

Grand Canyon in Arizona with structurally controlled drainage patterns.

Southern Appalachian Mountains in Tennessee with highly deformed metamorphic rocks of the Piedmont and sedimentary rocks of the Cumberland Plateau. Old crystalline rocks of the Great Smoky Mountains.

Glaciers - Valley glaciers in Alaska

Fluvial Processes - Colorado River, Arizona - the structural control of the river and its tributaries. Basin and range structure on the west.

Junction of the Mississippi and Ohio Rivers, with abandoned courses, meanders, meander scars. The boundary of glaciation as an east-west trending line.

Oxbow-lakes, meander scars and cut-offs on Mississippi River and Red River.

Trellis drainage patterns in Kansas highlighted in imagery by a light snow fall.

Modified dendritic drainage patterns in the Bighorn Basin of Wyoming as outlined by snow. Parallel drainage patterns.

Flood on Mississippi River in 1973, with possibility of before and after satellite image comparison of flooded areas along the Mississippi River.

Surface water movements in Florida Everglades. Surface flow instead of organized stream patterns. Effects of construction of causeway across portions of the Everglades.

Coastal Processes - Barrier Islands of the east coast, with the fragile environment of these islands and their enbayments. Urban development on these islands and the effects of storms.

High Altitude Aircraft Data - NASA has been flying high altitude aircraft over the U.S. since 1969 for research purposes in earth resources studies. This data is photographic and generally is color infrared at an altitude of 60,000 feet. Each frame of photography covers about 289 square miles or 17 miles on a side and is an excellent tool for vegetation, drainage, land use, soils, and geologic analysis. The original size of the data is primarily 9x9 inches and can be enlarged 2x, 3x or 4x as standard enlargements.

Remote Sensing - Basement Tectonics - Linears

The types of ore deposits referred to as "Mississippi Valley" are widespread, geographically and stratigraphically. They have probably produced 60 to 70 percent of the barite, fluorite, lead and zinc produced in the United States. The domestic districts that are of this type include the Tri-State (Missouri, Oklahoma, Kansas), Appalachian (Friendsville, Pa.), Austinville-Ivanhoe (Virginia), East Tennessee, Sweetwater, Cartersville (Georgia), Joplin and Southeastern Missouri districts, West Kentucky-Illinois, Central Tennessee, etc. In Europe it includes the Pennine district (Great Britain), Silesia (Germany and Poland), Ireland, Sardinia, etc.; in Africa the Algerian-Moroccan district; in Soviet Asia those of the Russian Platform (Ukraine), Kazakhstan, Georgia, and Siberia.

There are certain features of these type deposits that are generally agreed to by students familiar with them:

1. There are no obvious igneous source rocks in many districts.

2. The large deposits (but not all deposits) occur in platform carbonates.
3. The mineralogy of a given deposit or subdistrict is relatively simple, the typical predominant minerals are one or more of these: barite, galena, sphalerite, and fluorite. However, deposits of this type also contain Cu, Cd, In, Ge, Ga, Co, Ni, Ag, Fe, Mn, Hg, and S, again no one deposit has all of these, but collectively the class does. Less well known is the fact of abnormal concentrations of Be in the pre-Knox lead, zinc, and manganese deposits in the Southern Appalachians. Precious metal values are very small.
4. The host rocks are characteristically little altered and the gangue is simple: quartz, calcite, and dolomite.
5. The apparent age of the leads is discordant; i.e., the lead isotope ratios are "J" types.
6. The deposits in many instances occur in relatively structurally simple regions, but practically all are situated near major positive regional elements.
7. The major deposits are confined to particular stratigraphic units or facies within a stratigraphic unit; but smaller deposits in the district occur throughout several formations.
8. Major faults do not localize ore and in many districts post-date the ore, but smaller faults and fractures may be important ore controls.
9. Paragenesis generally is multistage, there are several ore-forming episodes.

10. The stratigraphic sequence contains sedimentary breaks ranging from diastems to major unconformities.
11. The most favorable areas within the thick carbonate sequences are the deposits flanking uplifted elements, areas of facies contrast or lithologic variation especially intertonguing limestone and dolomite or "dirty" sand and carbonates.

It is possible to add additional geologic factors that commonly, but not necessarily, invariably accompany this type deposit regionally:

12. Cryptoexplosion structures
13. Magnetite-rich basement rocks
14. Major shear zones or mobile zones in the basement rocks.

Any theory of genesis and any soundly based exploration effort must rationalize these factual characteristics.

Some of the data rules out certain theories, is permissive of some, and is simply not apropos to yet others. There are certain implications of the facts:

1. The mode of occurrence in some deposits or portions of a district permits the possibility that the deposits are syngenetic, i.e., deposited with the host rocks; but when the district is reviewed in its entirety it is obvious the ore is epigenetic and post-lithification.
2. It also becomes apparent that the ore controls do not involve the abstraction "reactivity" of the host rock so often appealed to as an explanation of ore localization. Ore is found in a variety of lithologies

including shale, sandstone, and carbonates. Equally, replacement (closely allied to "reactivity") is a minor feature. The major ore localizer is open space. A "favorable bed" is favorable because it contains open spaces.

3. Finally, there must be a source of ore ions, a connection from the source to the open spaces, and these must be related in time as well as spatially. It is the source that has created the main arguments about these deposits, and to a smaller degree arguments over the traps.

It is possible that the essential trap requirement is open spaces and that replacement is a minor element in ore localization. This premise can provide an explanation of why carbonates contain large volumes of the ores, sandstones smaller ones, and shales yet smaller one. Carbonates, especially shallow shelf deposits, are subject to being permeable for a variety of causes, other lithologies are permeable by virtue of good sorting and optimum size of grains in the instance of sands, or must be opened tectonically in the instance of shale or sand. But a shelf limestone can be permeable because (a) it is a reef with initial high permeability, (b) it is a reworked sorted and clean lime sand (oolite or calcarenite), (c) it is fractured tectonically, (d) it has been attacked by ground water solutions and opened along joints and bedding or so thoroughly stopped as to produce collapse breccias, or (e) the slightly lithified sediments have been brecciated by submarine sliding as the carbonates accumulated on the gently sloping shelf. Examples of all of these varieties of open space structure may exist in various of the Mississippi

Valley deposits. Hence, there would be mechanisms that operate most effectively in carbonates over large areas to generate open spaces. The same processes either are not able to affect elastic materials at all or are able to do so only to a minor extent. For instance, shales do not form wide shatter zones when deformed, and as a rule neither do sandstones. Even though faults in carbonates may be relatively small, the channels provided tectonically can be expected to result in much open space being created by subsequent solution. The fact remains, however, that the most pervasive creation of open space is caused by initial permeability - reef or calcarenite facies - supplemented by post-depositional solution; not by tectonically produced fractures in fine grained dense carbonates.

The correlation with cryptoexplosion structures is less certain, as is that with major mobile zones in basement rocks. However, these occur in proximity to Mississippi Valley districts in enough examples that the pattern is not coincidental. The 1968 Basement Rock map of the USGS locates cryptoexplosion structures. Starting at Rose Dome in Eastern Kansas a very nearly straight line connects Rose Dome, Weaubleau, Decaturville, Hazelgreen, Crooked Creek, Furnace Creek, Avon, and Hicks Dome. If the major mining districts Tri-State, Pea Ridge, Boss, Bourbon, Lead Belt, Southeast Missouri and Kentucky-Illinois fluorspar are added to the picture, the proximity of mines, basement upwards and cryptoexplosion structures is obvious. Similarly, the Grovers Bluff structure, Wisconsin arch, and upper Mississippi Valley district show the same pattern. Geophysical data seem to show large linear (38° Parallel) lineation parallel the first group.

Closer to Tennessee, Wells Creek, Flynn Creek and Norris Lake peridotites from an interesting line that passes through or in close proximity to known mineralization in Smith and Jackson Counties, lead, zinc and barite on the Powell anticline, zinc in the Copper Ridge district (in part), barite in the Know near Rogersville, and barite and zinc in the Fall Brance district.

It is interesting to observe that the Missouri magnetite-hematite bodies (nine are known) occur in close proximity to the Mississippi Valley lead-zinc-barite districts, and that a large magnetic anomaly has recently been discovered in Smith County, Tennessee. Another parallel is found in the western panhandle of Newfoundland where zinc mineralization in Knox equivalents is flanked by a "tectonic" trend and gravity anomaly trend.

It has been pointed out that the enormous Pine Point deposits (N.W.T., Canada), although in a Devonian reef, lie where the Devonian overlaps the precambrian shield and along strike with a major zone mobility in the Shield rocks.

Perhaps basement uplifts controlled facies developments in younger carbonates so that permeable zones (reefs, calcarenites, alternating lithologies, ground water solution, slide brecciation, etc.) are extensively developed in the younger sediments. In places, and from the same forces deforming the basement, linear zones of shear developed in the basement. These basement uplifts and associated shear zones have been more or less active at intervals over long periods of geologic time. In some times and places the activity has been deep enough to allow explosive subterranean (cryptoexplosive) events to occur; in those cases

where other basic magmatic activity has emplaced iron oxides and sulfides from the cooling upwelling magma, a later state fractionation of the magma and opening of plumbing would almost certainly put zinc and lead ions into circulation (zinc is able to fill the lattices of feric minerals, but not orthoclase; so it is of basic rock derivation). This suggests an areal association of magnetite-hematite deposits in basement rocks, copper in somewhat younger rocks and lead-zinc-barite-fluorite (in about that order) in still younger beds - all having been derived from episodes related to the differentiation of magma and episodic fracturing giving the ore solution access to traps in superjacent rocks. For example, Precambrian iron ores, Upper Cambrian lead, zinc and Lower Ordovician to Mississippian lead, zinc and barite in the mid-continent. Also, magnetite in the Appalachian crystallines upper in younger Precambrian sediments; pyrite, galena, sphalerite and barite in the Early Ordovician.

The probability seems to be rather high that the Middle Tennessee district may be found to be not only the habitat of Mississippi Valley type ores, but to also contain commercial tonnage and grade iron ores beneath the sediments.

PART II

The idea set forth above is that deep fractures, perhaps penetrating into basaltic magma, are associated with the basement blocks forming regional domes. Those fracture systems continue to be active episodically for very long periods of geologic time. This is borne out by repeated seismic activity associated with

some of the Precambrian domes (Nemaha, Appalachians, and Wisconsin). If the activity is intense enough, cryptoexplosive activity may occur; at another level of activity, juvenile metal-bearing solutions flow up into overlying rocks and if traps are available from ore deposits. Because this pattern is long-lived, a stratigraphic zoning in accord with classic hypogene order of crystallization occurs. The ore mineralogy may also be controlled by the compositions of the basement rocks involved. This system may also result in subaerial or submarine effusions of metal-bearing solutions. An interesting speculation is that this latter phase is the explanation of the present Red Sea metallic brines (along the East African rift lineament) and Salton Sea thermal metallic brines (San Andreas fault zone). Perhaps an older analog is the Brevard zone and associated gold-tungsten-sulfides of the Piedmont.

Applying this concept means that it is necessary to envision conditions as they were at the time(s) of ore generation, not as they may have subsequently become.

Evidence for East-West Fractures

The Wells Creek and Flynn Creek cryptoexplosion structures define a nearly east-west line that, projected still further east, passes through the peridotite plugs on Norris Lake. This axis is analogous to one that extends from Southern Illinois, across Missouri, into Eastern Kansas. This Midwestern axis includes the Hicks Dome, Avon, Crooked Creek, Decaturville, and Rose Dome structures; and in the opinion of Snyder and Gerdemann, "...the remarkable alignment of the features and frequent association with

basic igneous rocks suggest that these structures are closely related in mode of origin and that they represent intermittent deep-seated faulting and intrusion through a long period of time".

Another suggestion that transverse fractures exist in the Southeast is provided by the plastic relief model of the Knoxville 1:250,000 quadrangle (AMS N17-1 Series 50lp). This model clearly portrays topographic lineations along the axes Old-Fort-Asheville-Bryson City-Fontana Lake; and Spruce Pine-Hot Springs-Newport. These topographic lineations athwart the regional strike contain several bodies of cupiferous sulfides, barite, and pyrrhotite, as well as basic igneous rock masses. It may be significant that the lineations are clear in rocks of Precambrian Age and obscure in areas of Paleozoic strata.

The suggestion offered is that these lineations are the traces of large faults of Precambrian Age that extend for great distances. Their original vertical displacements were probably large. These lines of weakness have been the loci of later, less intense, episodic, movements repeatedly in post-Precambrian time. It is further proposed that conjugate fractures striking N.45°E. and N.45°W. were developed as a consequence of the large east-west stresses. These conjugate fractures provided channels through which hydrothermal ore solutions migrated into the overlying rocks from the subjacent magma chambers or rheomorphic zones. Where such solutions found suitable reservoir conditions, ore deposits were formed. It is also suggested that the mineralogic nature of the ore deposits is a function of the geochemical character of the basement rocks involved.

The east-west zones are defined by the alignment of crypto-explosion structures, basic igneous rock bodies, major seismic areas, topographic lineaments in Precambrian outcrop areas, and abrupt pinch-outs of ancient sediments (as the Ocoee Series).

Drainage patterns, gravity and magnetic anomalies, and ore deposits have been used to define the conjugate fracture traces.

POSSIBLE BASEMENT CONTROL OF GEOLOGIC PHENOMENA IN TENNESSEE

Introduction

The recent recognition of major fracture systems in the crust has been an important development in knowledge of the Earth's architecture. First discovered in the floors of the deep oceans it is now believed continental extensions of such fractures exist, and explain the Afro-Asian rift zone and various geologic features of the Western United States.

Some students of ore deposits suggest that such fracture systems, rooted in the "basement", may be responsible for the development of major mineral districts. For instance, Billingsley and Locke and subsequently Sims, Moench, and Tweto of the U.S. Geological Survey suggested in various papers that a relationship exists between very old zones of structural weakness and ore deposits in the Colorado mineral belt. Concurrent interest in cryptoexplosion structures led to papers that explain such structures as related to deep seated fractures and zones of alkalic igneous activity. It is noteworthy that in many instances these structures lie in areas containing Mississippi Valley type ore deposits. As is true of the fracture systems and cryptoexplosion structures, there has been a renewal of strong interest in this class of mineral deposits, especially following new major discoveries in Southeast Missouri, British Columbia, and Middle Tennessee.

The purpose of this discussion is to outline an hypothesis that ore deposits in Tennessee, and perhaps other geologic

phenomena are in fact related; that the connecting features are fracture zones in the basement rocks. The discussion that follows is based primarily on geologic features in Tennessee and nearby areas. The preliminary and speculative nature of the ideas here presented is clearly recognized, and criticisms and suggestions are welcomed.

NOTES ON ORE CONTROLS AND A MECHANISM FOR MISSISSIPPI VALLEY TYPE DISTRICTS

Mining districts designated "Mississippi Valley type" are, and have long been, the principal sources of barite, fluorite, lead and zinc ores in the United States and elsewhere throughout the world. A large volume of literature is available describing this class of ore deposits, explaining their habitat, and invoking genetic models for them. The quality of this literature is notably uneven, much of it demonstrably erroneous, and much of it restricted to detailed description of one aspect of the problem, or to a single mine, or even a single stope. Little literature deals with fitting these geologic phenomena into their geologic context and relating them to other geologic features regionally. In general, mining and mineral exploration geologists have failed to view an ore deposit as a feature arising from regional geologic history - that is, as a response to geologic environments. So regarded, these deposits become an expectable and rationally consistent member of a series of phenomena arising from known processes acting in environments and on materials known to occur naturally. This presentation, if governed by the constraints that these criteria (known processes, known environments, and known materials fitting into a logical pattern), must limit the model.

Characteristics of Mississippi Valley Ore Deposits

The following short list of characteristics believed to be significant to Mississippi Valley ore deposits will serve

as a basis for this discussion:

1. Absence of igneous rocks that are potential sources of the ore solutions.
2. Simple mineralogy.

Only a few minerals occur in a given district; however, collectively the variety of minerals from many such districts is expensive. Galena, sphalerite, barite, and fluorspar (principal), copper, cadmium, indium, germanium, gallium, cobalt, nickel, silver, iron and sulfur (subordinate). Wall rock mineralogy and alteration are also simple though the latter may be pervasive. A given mineral assemblage characterizes each district. Galenas characteristically yield anomalous lead isotope percentages (the "J-lead" problem).

3. The leads contain small percentages of precious metals.

Silver values are low and gold is almost unknown.

4. The major deposits occur in carbonate host rocks; however, other lithologies are mineral bearing.

5. The mode of the ores is replacement and open-space filling.

6. Common occurrence in areas of "passive structure".

This restriction is not universal; and "passive" is a relative term. In many instances, e.g., the Appalachian Valley and Ridge, the ore emplacement appears to have preceded structural deformation.

7. "Shallow depth"...occurrence at shallow depth is not as universal as formerly believed. In fact, oil test bores have encountered Mississippi Valley ores at depths exceeding 5,000 feet in Kansas.

8. "Relation to positive structures"...Many major districts are situated adjacent to or associated with major positive structural elements, e.g., Blue Ridge anticlinorium, Cincinnati Arch, Wisconsin Dome, etc.
9. "Evidence of solution activity"...Numerous districts show evidence of pre-ore solution action preceding ore deposition, or occurring concurrently with introduction of the ore.

Other features may be added in a discussion of the Southeast Missouri district:

1. Mineralization (some of small volume) ranges throughout the stratigraphic section. The mineralogy is different at various stratigraphic levels.
2. Major ore zones are restricted, generally, to a few hundred vertical feet of strata in a given district.
3. The ores are epigenetic (vis a vis the hosts).

To the above lists the writer would add these items:

1. Mississippi Valley districts occur in regions that in many instances contain cryptoexplosion structures and/or explosion diatremes.
2. Alkaline igneous rocks are generally known to occur in proximity to such districts.
3. The older, commonly "basement", rocks in proximity to the districts are major producers of magnetite and/or hematite.

The writer would also append these comments:

1. The dominant mode of the ores is everywhere open-space filling. The importance volumetrically of replacement has been over emphasized in the literature.
2. Evidence is increasing that mercury should be added to the list of species associated with Mississippi Valley ores.
3. Most, if not all, districts contain several generations of ore minerals.
4. Mississippi Valley districts are developed in strata overlying-"basement" surfaces that (where data are available) have notable vertical relief.

Mechanism Proposed to Explain Mississippi Valley Deposits

The writer proposed that Mississippi Valley ore deposits are one of several phenomena that have (and are) produced as a consequence of deep-seated fractures that are major elements of crustal architecture. These fractures are believed to have originated as early as Precambrian time, but to have been the loci of recurrent movement episodically over long time intervals. Depending upon the intensity of movement, depth of crustal penetration involved, type of deep-seated conditions involved, and thickness and character of overlying strata at the time of movement, various sorts of results are produced. If such material, either by upward movement of magma or by descent of phreatic water, produces steam a cryptoexplosion structure forms. The earlier (and later deeper buried) formed rocks are most likely to be enriched in iron; as a consequence, magnetite/hematite bodies are

formed and it thus follows that positive gravity and magnetic geophysical anomalies are created. Minor movements serve to produce joint and fracture systems in superjacent rocks. This produces stream flow and topographic lineations transverse to regional strike; especially in Precambrian terranes. But significantly to the purpose of this paper, such activity as this provides a source or ore mineral ions (the magma chambers) a plumbing system (fractures in both "basement" and superjacent strata) through which ore solutions can migrate to accumulate in suitable traps or reservoirs. The prolonged and episodic nature of this activity accounts for such items as variations in mineralogy with stratigraphic position (high temperature minerals below, low temperature minerals above), repeated episodes of ore emplacement, and discordant ages of lead isotopes (a result of the mixing of galenas of various geologic age). The mechanism also accounts for linear arrays of geologic features of the types described. Such linear arrays commonly are aberrant to regional strike and include bodies of mafic igneous rocks that may or may not crop out.

Application of this working hypothesis is most advanced in Tennessee; but there is excellent reason to believe it has much wider application. The delineation of major fractures in many areas shows there is abundant evidence for east-west zones. These are believed to be major high angle faults of Precambrian Age. Subsidiary sets of fractures striking N.45°W. resulted from the stresses producing the east-west faults. The distribution of ore districts (at least in Tennessee where better data is available)

suggest the main deep control is the intersections of the 45-degree lines and that the northwest striking zones are favored more than the northeast-trending ones.

However, favorable the conditions obtaining in the buried "basement" rocks no ore deposit will be produced unless the ore solutions encounter a trap. Equally, the extent of the trap will govern the size of the deposit formed--small trap, small deposit; large trap, major deposit. This simple and obvious fact is believed to explain why carbonate host rocks are commonly the preferred habitat for large ore deposits. Because open-space filling is the chief mode of Mississippi Valley ores and because such rocks may be permeable for several reasons (initial permeability, post-depositional removal of soluble constituents, tectonic breaking, sliding during deposition, any combination of these), carbonates and particularly restricted zones in carbonate sequences often present large volumes of open spaces to migrating ore solution. In contrast, clastic or massive igneous bodies can be opened only by tectonic activity which generally produces small discontinuous open spaces.

Particularly favorable conditions are to be expected in carbonate environments. These conditions occur where evaporites formed as part of sedimentary cycle (i.e., dolomite-anhydrite association) with subsequent removal of the evaporites and collapse breccias formation, and where alternating sequences of limestone-dolomite have formed follow by differential solutional phenomena as above. They also occur where paleoreefs and carbonate basins resulted in formation of permeable reef masses,

reef detritus, and penecontemporaneous sliding of lithified material to form breccia bodies, and where zones of permeable carbonate sands are bounded by impermeable beds. Examples of all these varieties of secondary control are believed to exist in various districts. From this analysis of the development of carbonate permeability it is believed the favorability of regional positive structures is explained. It is where such structural elements are overlapped by carbonate sedimentation that reefs, evaporites, and submarine brecciation may be expected.

Ideally, then, the combination of deep seated fractures, tectonic activity along the fractures (even very mild activity), and an overlying blanket of permeable material, especially carbonates, provides the setting for an ore deposit. For economic development the ore horizon should be now located at 2,500 feet or less below ground level. Parenthetically, this economic consideration may influence to an unknown degree the apparent favorability of positive elements as it influences exploration activity. It should also be noted that paleo-erosional intervals (disconformities) following carbonate deposition afford opportunity for the formation of desirable traps. Thus unconformities also are useful in delineating favorable zones.

Application to Southeastern United States

The intersection of the conditions sketched in the genetic model above occur in several areas of the Southeast. That such is the case in the Valley and Ridge and Nashville Basin in

Tennessee is obvious from exploration and mining development. The writer believes it is also true that similar favorable, but less obvious, conditions are present in the Lexington Basin of Kentucky (but on its higher parts); beneath the cover of Mesozoic and Tertiary sediments in Western Tennessee and Kentucky, especially where the younger sediments directly overlies the Know Group or lower Middle Ordovician units; in the Valley and Ridge, more deeply dissected Highland Rim, and along the northern edge of the Coastal Plain of Alabama.

Exploration Techniques

A preferred approach to the search for ores of the Mississippi Valley type begins with an analysis of regional geologic conditions as sketched above. Remote sensing can be very helpful in this analysis. Further definition of the traces of the basement controls is apparently possible by geophysical methods. Existence of shallow target zones (within the zone of circulating water) is amenable to dithionite method geochemical exploration; and limited evidence suggests that mercury trace analysis by atomic absorption may be useful in instances of deeper ground.

Highways and Landslides

By far the most exasperating landslides in Tennessee have occurred along Interstate 40 near Rockwood. Here, there have been more than 20 major slides in a 4 mile (6.4km)--long section. All have involved the "PC Complex".

Once the failure mechanism for each slide is understood, the engineer can then select the appropriate remedial measure. A

treatment for one slide may not be adequate for another or, worse, may actually accelerate movement.

Since the original alignment and gradient of the roadway were being held, remedial measures at Rockwood include: drainage; partial to complete removal of slide areas; partial removal and restraint; or "total" restraint. In the case of restraint, two methods have been utilized: rock buttresses and gabions.

The rock buttress

A rock buttress is a free-draining gravity structure consisting primarily of large blocks of non-degradable sandstone or limestone. At Rockwood the specifications call for 50% of the material to be greater than one cubic foot, with no more than 10 percent passing a No. 2 mesh sieve; it must be free of coal, shale, and soil materials.

Because of its free-draining characteristics, the rock buttress works well in restraining colluvial slides. Movement is prevented by restraint while at the same time allowing large quantities of water from the colluvium to seep or percolate through unrestricted--thus reducing the likelihood of "ponding" and pore pressure build-up.

Any large buttress must be founded on in-place (residual) soils or sound material below the colluvium. Placing such a massive structure directly on the colluvium would cause failure through shear or subsidence.

The greatest disadvantage of a rock buttress is that, because of its wide base, it requires a much greater area than other types of restraint structures. Hence, they must always be placed

at the toe or foot of the slide rather than at the middle or crown.

Another Restraint Structure: The Gabion Wall

Another type restraint structure being used in Tennessee is the gabion wall. It is a free-draining, heavy, monolithic gravity structure consisting of wire mesh baskets (gabions) filled with coarse non-degradable rock. The gabions are made of zinc-coated No. 11 steel wire, and range in size from 3x3x36 ft. (0.9x0.9x0.11m) to 3x3x9 ft. (0.9x0.9x2.7m). Each basket is secured to an adjacent basket with a tie-wire, then loaded in place with rock.

A gabion wall was chosen for this project in lieu of concrete retaining walls not on the basis of costs, but because it provides the flexibility needed to cope with differential settlement. The gabion wall also has excellent permeability, needed to drain the restrained material. Finally, it requires less lateral space than a rock buttress and therefore is used where space is limited. Construction cost of the gabion walls at Rockwood compare favorably with rock buttresses-though cost alone cannot be the prime consideration in determining which type structure to use.

Draining Area to Prevent Slides

Partial removal or total removal involves removing part or all of the unstable material from the failing cut or embankment (fill) area. For embankments (fills), the removed material must be replaced by more stable material. Most highway landslide

problems in Tennessee have occurred on the slope of the escarpments of the Cumberland Plateau.

The surface rocks of the plateau are largely sandstones, siltstones, and shales, with occasional interbedded coal layers. Most of these rock types, being moderately to highly resistant to the processes of weathering, produce shallow soils. Along the slopes of the escarpments, the materials that most affect roadway and slope stability are clay shales, colluvium, and water. The clay shale involved in most major landslides is the Pennington Shales, which varies from 200 to 500 ft. (70 to 152m) in thickness.

Understanding Slope Evolution

One cannot consistently solve landslide problems without understanding how the slope materials got there in the first place; and what can be expected when these materials and conditions are tampered with. To get a somewhat simplified understanding, let us assume that at some past geological time, the escarpment was totally base--devoid of vegetation, soil, loose rock, etc. At a more recent point in time, this smooth slope began to erode with troughs, gullies and ravines being formed all across its face, becoming wider and deeper toward the base. As time passed, these gullies and troughs began to be refilled with materials continually being eroded from the upper slopes. Huge chunks of the sandstone would become dislodged from their stratified positions at the top of the escarpment and fall or roll downslope, coming to rest in the troughs. This process continued until the gullies and troughs were filled and the entire base of the slope covered with debris that had fallen or eroded from the upper slopes.

In the meantime, the rocks--the shales--in the lower slopes, now covered with debris, began to weather in-place through leaching, slaking, etc., until their "rock characteristics" became obliterated and the upper portions of these materials were transformed to clayey soils. These clays, being formed under several hundred feet of debris, were fairly well consolidated; hence, they developed reasonably high internal strengths.

On the other hand, the debris (colluvium), because of the erratic manner in which deposited, does not develop a high degree of consolidation; yet its internal strength is fairly high because of its heterogeneous nature. Because of the coarse and loose unconsolidated nature of this debris, it has high permeability.

Still later in the chain of events, the debris (colluvium) begins to settle and shift downslope. These slides occur most frequently during periods of heavy precipitation when water, percolating down through the material, reaches the impervious clays and shales. Movement is due to the increased weight of the debris because of the added water; and to saturation of the debris-shale interface. Slides are especially active where the sides of the troughs and gullies are steepest.

By now, vegetation begins to form on the slopes and the processes that had been active in developing the landscape begin to slow down. There begins now a period of relative quiescence which carries up to the present. The underlying shales continue to weather through leaching and slaking but not as dynamically as before. Slides still occur sporadically; the more recent ones (past 50 to 200 years) can be identified today by abrupt changes in their growth processes.

Present Condition of Slopes

Most of the Cumberland Plateau escarpment is in a delicate state of equilibrium. In some areas, the safety factor against failure in the natural slope is not much above 1.00. If the load at the top of a slope is increased and the toe support not increased, we can expect the slope to fail. Or if the toe support is reduced, we can expect failure.

Along Interstate 40 at Rockwood, Tennessee, for example, fills were placed across marginally stable areas; the slope failed under the increased load. In cut areas, where toe support was removed by excavation, the upper slope failed. The same could be said for all land-slides; they result from increased loads at the head or reduced support at the toe.

Practical Implications

The most significant thing about the Pennington shale, engineering-wise, is that it weathers and breaks down rapidly to a very weak, highly plastic, impervious clay. These properties are especially significant where the formation occurs in a slope overlain by colluvium. Colluvium is a heterogeneous mixture of clay, silt, sand, rock fragments, and boulder-sized particles that lies as a veneer (from 5 to 50 or more ft. thick) over the escarpment slope. Since it was produced by the weathering of the shale and sandstone rock making up the slope, the colluvium is a very "young" material in terms of the geologic clock. It is highly permeable, whereas the clay shales and residual clays are virtually impermeable. This allows ground water to collect and sometimes become trapped along the colluvium-shale interface

and within the soil mass itself is overcome, and failure occurs.

One must be aware of the subsurface troughs throughout a project area. For it is the angle of slope along the interface between the colluvium and shale or clay within these troughs that controls stability-rather than the cohesion and angle of friction of individual materials. Failure may also result where subsurface drainage along this interface is impeded by the consolidation of these materials from the weight of an overlying fill.

For brevity, the "PC Complex" will denote the entire material-condition grouping along the escarpments; this term includes the three principle materials (Pennington shale, colluvium, and water).. as well as the usual associated conditions (rugged topography, high relief, unpredictable subsurface drainage patterns).